MULTI-MEGAWATT SPACE NUCLEAR POWER GENERATION

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SUMMARY

Capability for multi-megawatt nuclear power generation in space is examined and promising options identified. Nuclear power systems will generate approximately three times as much power as chemical systems, at the same rate of expenditure of consumables (H_2 for open-cycle, high-power nuclear systems, H_2/O_2 for chemical systems). In addition, the nuclear power system exhaust, if used for platform thrust, will have approximately twice the specific impulse of chemical systems.

Three reactors options are compared — NERVA and two particle bed reactors, the Fixed Bed Reactor (FBR), and the Rotating Bed Reactor (RBR). The particle bed reactors appear to have advantages of much faster startup capability, and reduced concern about reliability and fuel element failure. They also have somewhat smaller size and lower weight, but the benefits are marginal in terms of overall system weight.

The FBR appears as the most attractive overall reactor system. It would operate bimodally, generating cw in the hundreds of kW(e) for station keeping, surveillance, defense purposes, etc, and high power, in the hundreds of MW(e), for pulsed energy devices.

The FBR would use HTGR-type particle fuel, contained in a annular bed between two porous frits. Helium would be used as a closed-cycle coolant for cw generation, and hydrogen as an open-cycle coolant for pulsed electric generation. The FBR could startup and shutdown in a few seconds. Overall reactor size is ~1 m^3 and overall reactor weight 2 to 3 metric tons.

Closed-cycle He (or He-Xe) turbines would be used for cw generation and open-cycle H_2 turbines for pulsed generation. MHD does not appear attractive

compared with turbines because of much lower efficiency and its less developed state technology. MHD does appear necessary for power levels above a few hundred megawatts.

Superconducting ac generators of the type under development by APL would be used. They offer very lightweight and rapid startup capability.

A 200/200 FBR Bimodal Power System is described. This would have a cw output of 200 kW(e) (which could be increased to 400 kW(e) with relatively small modifications) and a pulsed output of 200 MW(e). Total integrated power capability for the pulsed mode is 100 MW(e) hours, with a H_2 consumable requirement of 27 metric tons.

The reactor and all power equipment are contained in a unitized framework (16 meter length, 3 meter maximum width) weighing ~20 metric tons. This power train could be carried in the Shuttle cargo bay or on a Shuttle derived cargo vehicle, together with the H_2 tank (6 meter diameter, 13 meter long) and the payload.

Technology status of the reactor and power equipment is reviewed and RD&D requirements identified. Development would appear to be of an engineering nature, with no scientific feasibility issues to be resolved.

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1. OPTIONS FOR HIGH POWER IN SPACE

Why Nuclear?

Nuclear reactors appear very attractive for high-power generation on space platforms for several reasons:

a. Nuclear reactors will be required anyway for cw station keeping power.

b. High-power nuclear systems will consume much less expendables than chemical power systems.

c. H_2 exhaust from reactors has higher specific impulse for thrust than a chemical source.

d. The reactor can operate bimodally (high power + low power), eliminating a second heat source.

With regard to the first point, cw power levels in the range of ~100 kW(e) to ~1 MW(e) will probably be required for space platforms. Uses will include surveillance, orbit maneuvering, operating defense systems, communications, etc. These power levels are far beyond chemical or solar capabilities. They can be met with closed-cycle nuclear reactors.

Figure 1.1 compares chemical and nuclear high-power systems. Closed-cycle reactors at very high power, i.e., on the order of a hundred megawatts, will require considerable development, but appear feasible. For the near-term, however, the choice will likely be between open-cycle nuclear (H_2-cooled) and open-cycle chemical (H_2/O_2).

FIGURE 1.1

TRADEOFFS BETWEEN HIGH-POWER CHEMICAL AND NUCLEAR POWER SYSTEMS

	CHEMICAL	NUCLEAR
CLOSED-CYCLE CAPABILITY	NONE	POSSIBLE WITH ADVANCED SYSTEMS
OPEN-CYCLE CONSUMABLE EXPENDITURE 100 MW(e) hrs, METRIC TONS (40% EFFICIENCY, T~2500 K)	80	24
CONSUMABLE EXPENDITURE FOR SYSTEM TESTS (10 yr, 3 MONTH INT., 100 MW(e)) METRIC TONS, 1 MIN TEST	54	16
POWER SYSTEM DRY WEIGHT, METRIC TONS (INCLUDING TANKAGE) FOR 100 MW(e) SYSTEM	16	15
START-TIME, sec	1 to 2	2 to 3
NUMBER OF RESTARTS	HUNDREDS	HUNDREDS
SPECIFIC IMPULSE EXHAUST, sec	450	800
RD&D TIME	SEVERAL YEARS	7 to 10 YEARS
ACCEPTANCE	NO PROBLEMS	POTENTIAL OPPOSITION

An open-cycle chemical power system will consume much more fuel than a H_2 cooled reactor system. The ratio for the two options depends on operating temperature and efficiency (thermal-to-electric). Figure 1.1 shows 80 metric tons of H_2/O_2 required for a 40% efficient power cycle with a 2500 K turbine inlet temperature (achieved by GE in 1960), assuming 100 MW(e) hours of integrated output. Hydrogen consumption for the nuclear system is much smaller, 24 metric tons. Besides consumables required for the missions of interest, additional consumables will be required for periodic tests of the platform. These can easily equal or exceed that required for the actual mission.

In the example shown in Figure 1.1, a 10-year system life is assumed with a 1 minute test every 3 months. The integrated consumable expenditure for tests is then 2/3 of the amount required for the nominal 100 MW(e) hour.

System dry weight is essentially equal for both the chemical and the nuclear systems, since the weight of the reactor and shield is offset by the additional tankage weight for the chemical source. In the example shown, tankage weight is taken as 10% of consumable weight (this is probably too small), integrated capacity is 100 MW(e) hour, and output power level is 100 MW(e). Specific masses of the power system are assumed equal at 0.02 kg/kW(e) for superconducting generators and 0.02 kg/kW(e) for turbines, based on high-power scaling studies.

Both chemical and nuclear systems can be designed for fast start capability, i.e., several seconds, and can start and stop many times. Nuclear systems will have an important advantage in their ability to discharge hot gas with a substantially higher specific impulse than chemical systems, e.g., ~800 seconds vs ~450 seconds. This increases rapid orbit maneuvering and evasive action capability.

Nuclear power systems will require longer development times than chemical systems, and do have the public acceptance problem. However, cw nuclear power systems will have to be developed anyway as part of the platform, so that having a high power nuclear system capability should cause only a small perturbation of development schedule and no extra public acceptance problem. Also, development of the weapons system itself will require a period comparable to that for the nuclear power system, so that a shorter development schedule for chemical-power systems appears of no particular advantage.

An interesting side point is the potential effect of exhaust gases on payload system performance. Background gas pressure can affect high-voltage electric systems, sensors, beams, etc. Hydrogen exhaust from a nuclear power system will have a considerably lower background gas pressure than H_2/O_2, due to its higher sound speed.

In summary, high-power nuclear systems do have operational advantages over chemical systems, and should pose no major scheduling or acceptance problems over those faced in developing the platforms that they power.

Why Open-Cycle Nuclear?

Figure 1.2 summarizes the relative advantages of open-cycle nuclear vs. closed-cycle nuclear. With present radiator technology for rejection of waste heat, the maximum practical cw power system will be a few megawatts (electric) at most. High-power cw systems will require development of a lightweight radiator such as the Liquid Droplet Radiator to be practical.

Even with lightweight radiators, high-power cw systems are a formidable engineering challenge. The breakeven point (equal weight) between open- and closed-operation is approximately two hours of integrated operation. Thus,

FIGURE 1.2

OPEN- VS. CLOSED-CYCLE NUCLEAR SYSTEMS

	OPEN CYCLE	CLOSED CYCLE
HEAT REJECTION	H_2 EXHAUST	RADIATIVE HEAT REJECTION
COOLANT	HOT H_2	HOT He
PRESSURIZATION	LIQUID H_2 PUMPS	COMPRESSORS
EFFICIENCY	~40%	~20 to 30%
MAJOR DRY WEIGHT COMPONENT	TURBINES/GENERATORS	RADIATOR
SYSTEM DRY WEIGHT FOR 100 MW(e), METRIC TONS	15	50 to 100
MAXIMUM INTEGRATED OPERATING TIME, HOURS	FEW HOURS	MONTHS
USEFUL EXHAUST FOR THRUST	YES	NO
SYSTEM DIMENSIONS	~10x2 METERS	~150x150 METERS (LIQUID DROP RADIATOR)
COMPONENT PACING DEVELOPMENT	1. TURBINE/GENERATOR 2. REACTOR	1. LIQUID DROP RADIATOR 2. REACTOR

open-cycle systems are a practical choice for platforms for the near-term, i.e., the next decade or so. For the long term, cw systems will probably be necessary.

Which Reactor Technology?

Reactor technology is discussed in more detail in the next section. Figure 1.3 compares the principal features of the three main options proposed.

All are direct gas-cooled systems. Other options, like liquid-metal cooled or in-core thermionics, do not appear practical for high-power usage. Their core size would be excessive, or they would require a large, heavy intermediate heat exchanger. Gas core reactors are of potential interest for high-power systems, both closed- and open-cycle, but are still at a very early stage.

The NERVA solid-core reactor was successfully demonstrated in ground tests over a decade ago. However, it was intended for direct nuclear rocket missions, and not for electric generation of the kind desired.

The FBR and RBR particle bed reactors are more recent concepts, and primarily oriented towards electric generation, both for open- and closed-cycle operation. These reactors use the particulate fuel of the type developed for HTGR reactors.

What Power Conversion Option?

The only practical power conversion options for high power are turbo/generators and MHD. Figure 1.4 compares the main features of these options.

Turbo/generators offer better performance than MHD and are more developed, and they would be preferred for high-power generation in space.

MHD at best will have a conversion efficiency of ~20%. For commercial applications, it is always viewed as a topping unit to be used with some type of bottoming cycle, e.g., steam turbine.

FIGURE 1.3

REACTOR OPTIONS

	NERVA	FBR	RBR
FUEL TYPE	SOLID RODS	SMALL PARTICLES (~600 MICRON DIAMETER)	SMALL PARTICLES (~600 MICRON DIAMETER)
MAXIMUM EXIT GAS TEMPERATURE	~2700 K	~2500 K	~3000 K
MAXIMUM ELECTRIC POWER CAPABILTIY (~40% EFFICIENCY)	~2000 MW(e)	~500 MW(e)	~2000 MW(e)
REACTOR WEIGHT FOR MAXIMUM POWER, METRIC TONS	~8	~3	~3
BIMODAL CAPABILITY (PULSED HIGH POWER + cw STATION POWER)	PROBABLY NOT	YES	NO
STARTUP TIME, SECONDS	30	2 TO 3	2 TO 3
LIMITING FACTOR	THERMAL SHOCK TO FUEL	PUMPS & SYSTEM CONTROL	PUMPS & SYSTEM CONTROL

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FIGURE 1.4

POWER CONVERSION OPTIONS

	TURBO/GENERATOR	MHD
EFFICIENCY, THERMAL-TO-ELECTRIC	~40%	~20%
INLET TEMPERATURE FOR PRACTICAL SYSTEMS	$1500 \leq T \leq 2500$ K	≥ 2800 K
INLET PRESSURE FOR PRACTICAL SYSTEMS	UP TO ~50 atm	≤ 20 atm
OUTPUT TYPE	HIGH VOLTAGE ac, UP TO ~100 kV	HIGH VOLTAGE dc, UP TO ~50 TO 100 kV
OUTPUT CAPACITY PER UNIT	UP TO ~100 MW(e)	≥ 50 MW(e)
EQUIPMENT SIZE	T&G EACH ~1 m^3	MHD CHANNEL ~1x1x8 METERS
TECHNOLOGY STATUS	CLOSE TO DEVELOPED	SUBSTANTIAL R&D REQUIRED
ISSUES	• SCALING TO HIGHER POWER • HIGH-TEMPERATURE TURBINES	• LIFETIME OF CHANNEL MATERIALS • (ELECTRODES & INSULATORS) OPERATION IN H_2 ELECTRICAL EFFICIENCY

Turbines will have considerably higher cycle efficiencies. For open-cycle space power generation, a compressor is not required, since the liquid H_2 feed would be pressurized by a pump, which consumes only a small fraction of the turbine output. This increases efficiency considerably, as compared to standard Brayton cycles with compressors.

Efficiency could be substantially greater than 40%. The GE "Hot-Shot" H_2/O_2 turbine cycle, for example, was estimated to achieve cycle efficiencies above 60%. However, to achieve these efficiencies, large pressure ratios are required across the turbine. While these are achievable in principle, since the turbine exhausts to space, in practice the number of stages and turbine size become excessive.

A cycle efficiency of ~40% appears practical, though a relatively large pressure ratio is still required, ~60/1. This will require a multi-stage turbine with an inlet pressure of ~50 to 60 atm and an exhaust pressure of 0.8 to 1 atm.

Inlet temperature capability of the power system is also very important for open-cycle space power systems, since it helps to determine how much consumables are required per unit electric output

$$(m_{coolant}/\text{unit output} \propto (\eta_{cycle} \cdot \overline{C_p} T_i))^{-1}$$

An equilibrium MHD generator operating on H_2 will require an inlet temperature of at least 2800 K (based on studies by R. Rosa) to function with 20% thermal efficiency. Turbines, of course, can operate at much lower temperatures. Here, the desire is to achieve the highest turbine operating temperature possible to minimize H_2 consumable expenditure.

With uncooled refractory metal blades, maximum turbine inlet temperature for long-life systems would be ~1500 K. Since only a few hours lifetime would be required, this could probably be substantially increased. Ceramic blading or carbon-carbon blading should allow temperatures well above 2000 K.

With cooled blades, turbine inlet temperatures of ~2500 K appear achievable. General Electric ran a 2-MW(e) H_2-cooled metal blade turbine at 2500 K turbine inlet temperature in the early 1960's. Blade cooling will reduce cycle efficiency somewhat, but only by a few percent.

Thus, inlet temperature capability for turbines should be comparable to fuel temperature capability, and can approach the levels contemplated for MHD. It has the important advantage, however, that it can operate below the minimum required for MHD if ~2800 K proves to place too much strain on the fuel.

With regard to the other factors listed in Figure 1.4, turbines also out perform MHD. Output is high voltage ac which is more desirable than dc, size is smaller, technology is considerably more developed, and there are fewer technical issues to be resolved. Materials, for example, is a very important question for MHD.

Why Bimodal Operation?

Figure 1.5 shows the general features of bimodal- and single-mode systems. Single-mode operation, i.e., two reactors, allows greater flexibility in the choice of power cycle and reactor design, but imposes extra weight and size on the system. A bimodal reactor, if practical, would be preferred, over two reactors.

As discussed in a subsequent section, the FBR reactor appears capable of operating on both He or H_2 with two separate turbine systems. The switch to the high-power mode could be made in a few seconds. There appears to be no bar to switching back and forth whenever desired, and the number of mode switches could be as large as desired.

FIGURE 1.5

BIMODAL VS. SINGLE-MODE GENERATION

	BIMODAL	SINGLE MODE
cw STATIONS KEEPING POWER	SEVERAL HUNDRED kW(e)	SEVERAL HUNDRED kW(e)
PULSED HIGH POWER CAPABILITY	$\geq$ 100 MW(e)	$\geq$ 100 MW(e)
NUMBER OF REACTORS	1	2
NUMBER OF POWER CONVERSION SYSTEMS	2	2
TYPE OF POWER CONVERSION	BRAYTON He TURBINE CYCLE + OPEN CYCLE H_2 TURBINES OR THERMOELECTRIC WITH HEAT PIPES IN REACTOR + OPEN CYCLE H_2 TURBINE	REACTOR A WITH OPEN-CYCLE H_2 TURBINE + REACTOR B WITH THERMIONIC OR BRAYTON He CYCLE OR HEAT PIPE/THERMOELECTRIC

2. HIGH POWER REACTOR TECHNOLOGY OPTIONS

As discussed in the previous section, three reactor approaches have been proposed for the high power regime:

a. NERVA,

b. FBR, and

c. RBR.

Figure 2.1 shows overall drawings of the principal reactors tested in the NERVA program. A number of reactors were successfully ground tested in the late 1960's and early 1970's. Although progress was good, the NERVA program was terminated in 1973 due to lack of a defined mission.

The NERVA reactors used graphite fuel elements (Figure 2.2) with UC_2 particles imbedded in the graphite matrix. The elements are hung from a grid plate at the inlet (cold) end of the reactor.

The graphite element has a number of holes to carry the H_2 coolant. All surfaces are coated with ZrC to protect against H_2 corrosion. The intgerity of the ZrC coating is crucial to the performance of the reactor, since graphite is attacked by hot H_2. Cracks in the coating due to thermal expansion effects or radiation damage could compromise reactor operability.

Figure 2.3 shows the main parameters for the reactor tests and Figure 2.4 the operating time/temperature history for the various reactors.

Although the reactors operated successfully, fuel element damage and cracking was observed in a number of instances.

A "second generation" NERVA, the "Small Nuclear Engine" was designed but not tested. Figure 2.5 shows the fuel element structure for this reactor. It had a central ZrH moderator cooled by the inlet H_2 and thermally insulated from the hot graphite fuel elements.

FIGURE 2.1

COMPARISON OF REACTORS TESTED IN ROVER PROGRAM

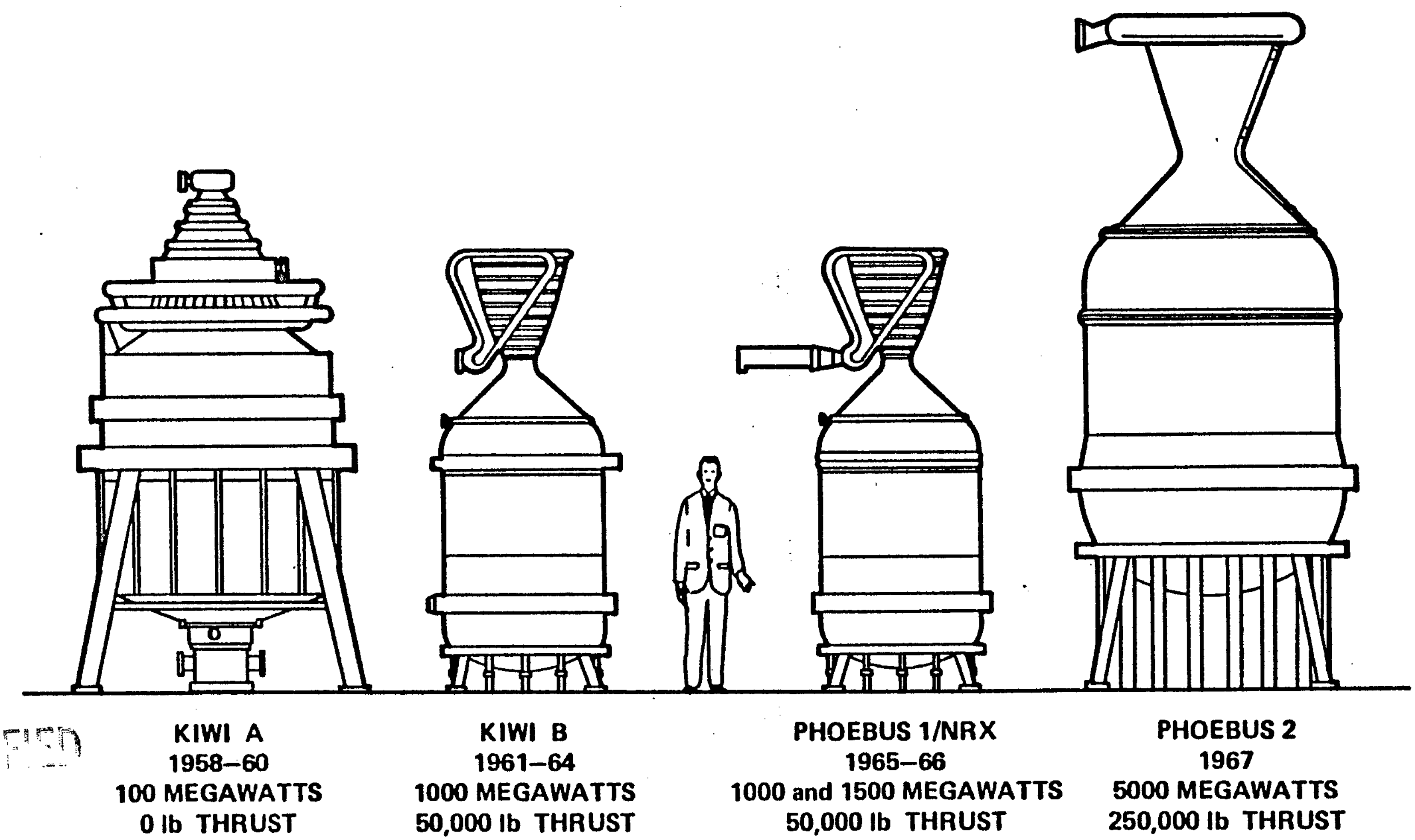

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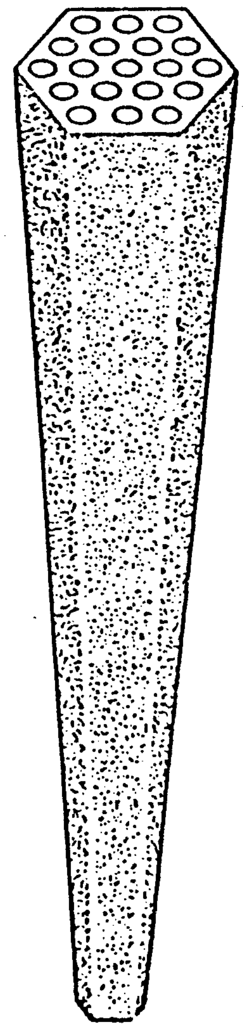
FIGURE 2.2

CUTAWAY OF REACTOR AND FUEL ELEMENT



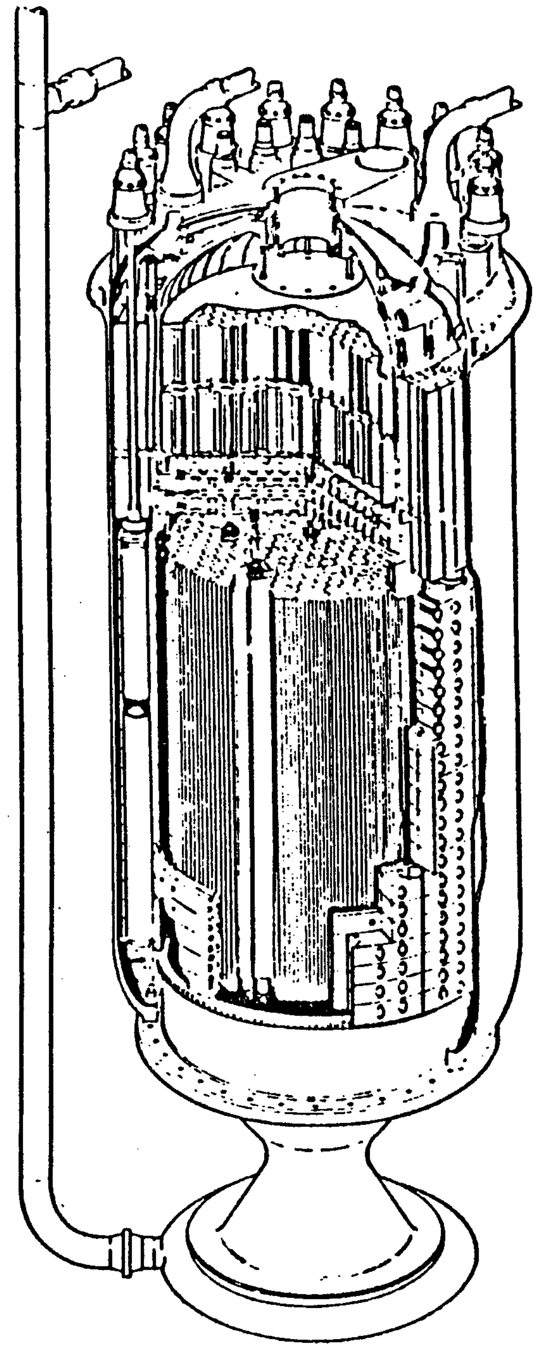


FIGURE 2.3

REACTOR SYSTEMS TESTS PERFORMANCE

	KIWI-4BE	NRX-A6	PHOEBUS 2A	PEWEE
REACTOR POWER (MW)	950	1167	4080	507
FLOW RATE (kg/s)	31.8	32.7	119.2	18.6
FUEL EXIT AVERAGE TEMPERATURE (K)	2330	2472	2283	2556
CHAMBER TEMPERATURE (K)	1980	2342	2256	1837
CHAMBER PRESSURE (MPa)	3.49	4.13	3.83	4.28
CORE INLET TEMPERATURE (K)	104	128	137	128
CORE INLET PRESSURE (MPa)	4.02	4.96	4.73	5.56
REFLECTOR INLET TEMPERATURE (K)	72	84	68	79
REFLECTOR INLET PRESSURE (MPa)	4.32	5.19	5.39	5.79
PERIPHERY AND STRUCTURAL FLOW (kg/s)	2.0	0.4	2.3	6.48

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FIGURE 2.4

OPERATING TIME vs TEMPERATURE FOR NUCLEAR ROCKET PROGRAM

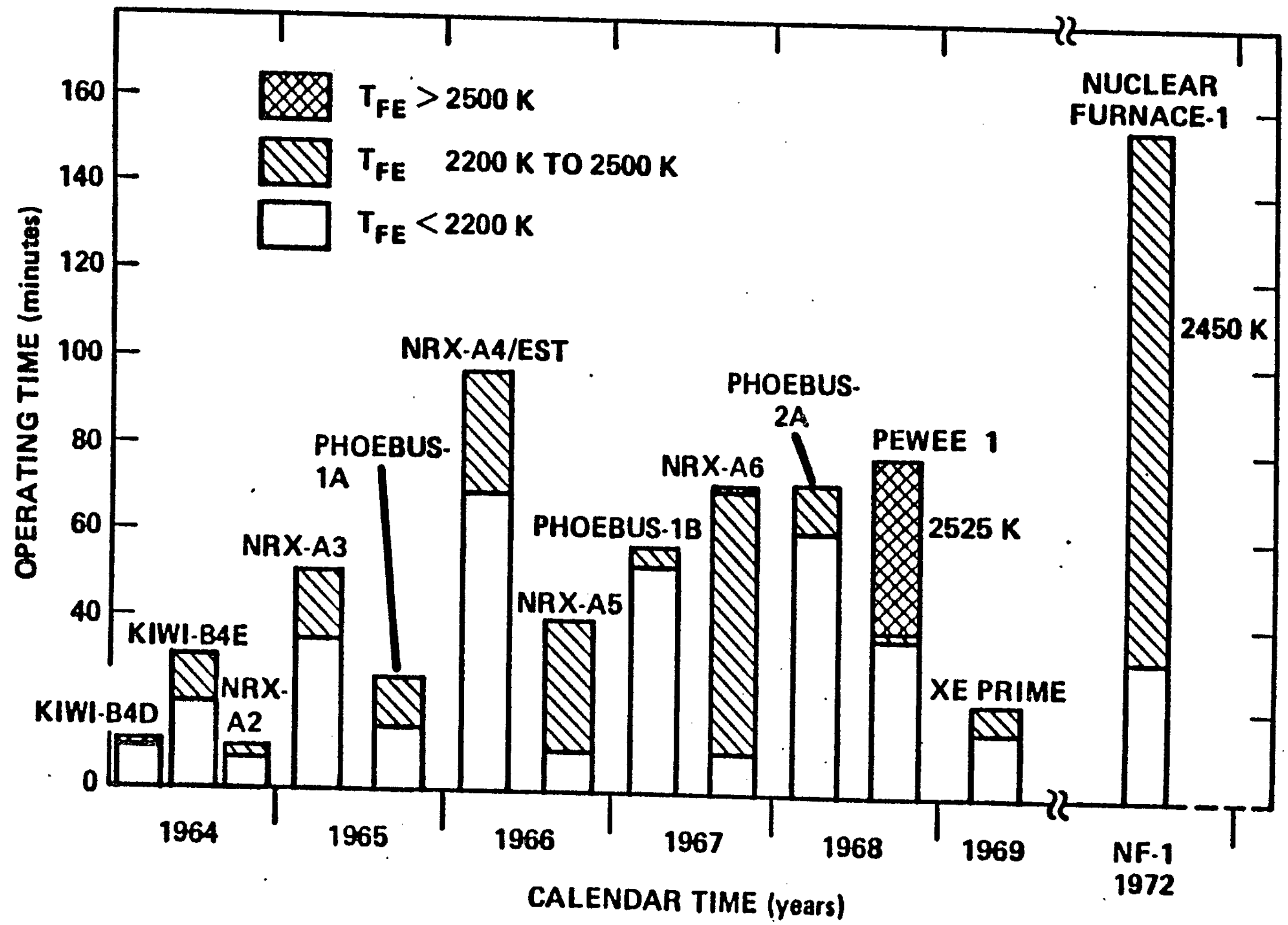

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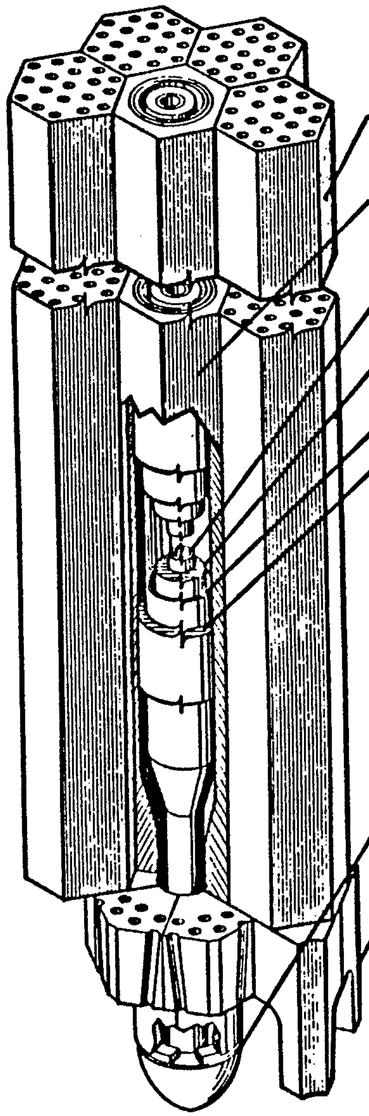
FIGURE 2.5

FUEL MODULE



FUEL

- **FUNCTION**
  - PROVIDED ENERGY FOR HEATING HYDROGEN PROPELLANT
  - PROVIDED HEAT TRANSFER SURFACE
- **DESCRIPTION**
  - ^{235}U IN A COMPOSITE MATRIX OF UC-ZrC SOLID SOLUTION AND C
  - CHANNELS COATED WITH ZrC TO PROTECT AGAINST H_2 REACTIONS

TIE TUBES

- **FUNCTION**
  - TRANSMIT CORE AXIAL PRESSURE LOAD FROM THE HOT END OF THE FUEL ELEMENTS TO THE CORE SUPPORT PLATE
  - ENERGY SOURCE FOR TURBOPUMP
  - CONTAIN AND COOL ZrC MODERATOR SLEEVES
- **DESCRIPTION**
  - COUNTER FLOW HEAT EXCHANGER OF INCONEL 718
  - ZrH MODERATOR
  - ZrC INSULATION SLEEVES

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The improved moderation achievable with the hydride moderator allows somewhat smaller reactors. Figure 2.6 shows power rating vs. weight for the various NERVA engines. The Small Nuclear Engine design lies below the scaling curve for the other graphite-moderated systems.

NERVA was intended for nuclear rocket applications and not for pulsed electric power generation. Maximum rate of temperature rise was ~80 K/second. Faster rates of temperature rise would be limited by thermal shock effects on the fuel elements.

At 80 K per second, the NERVA reactor would take ~30 seconds to reach an exit gas temperature of 2500 K, starting from a cold core condition. Because of the relatively large fuel elements, it appears doubtful that NERVA could start up in a substantially shorter time without damage to the fuel.

Other factors that could effect its capability for pulsed electric generation are:

a. Effect of fuel element failure on the turbine,

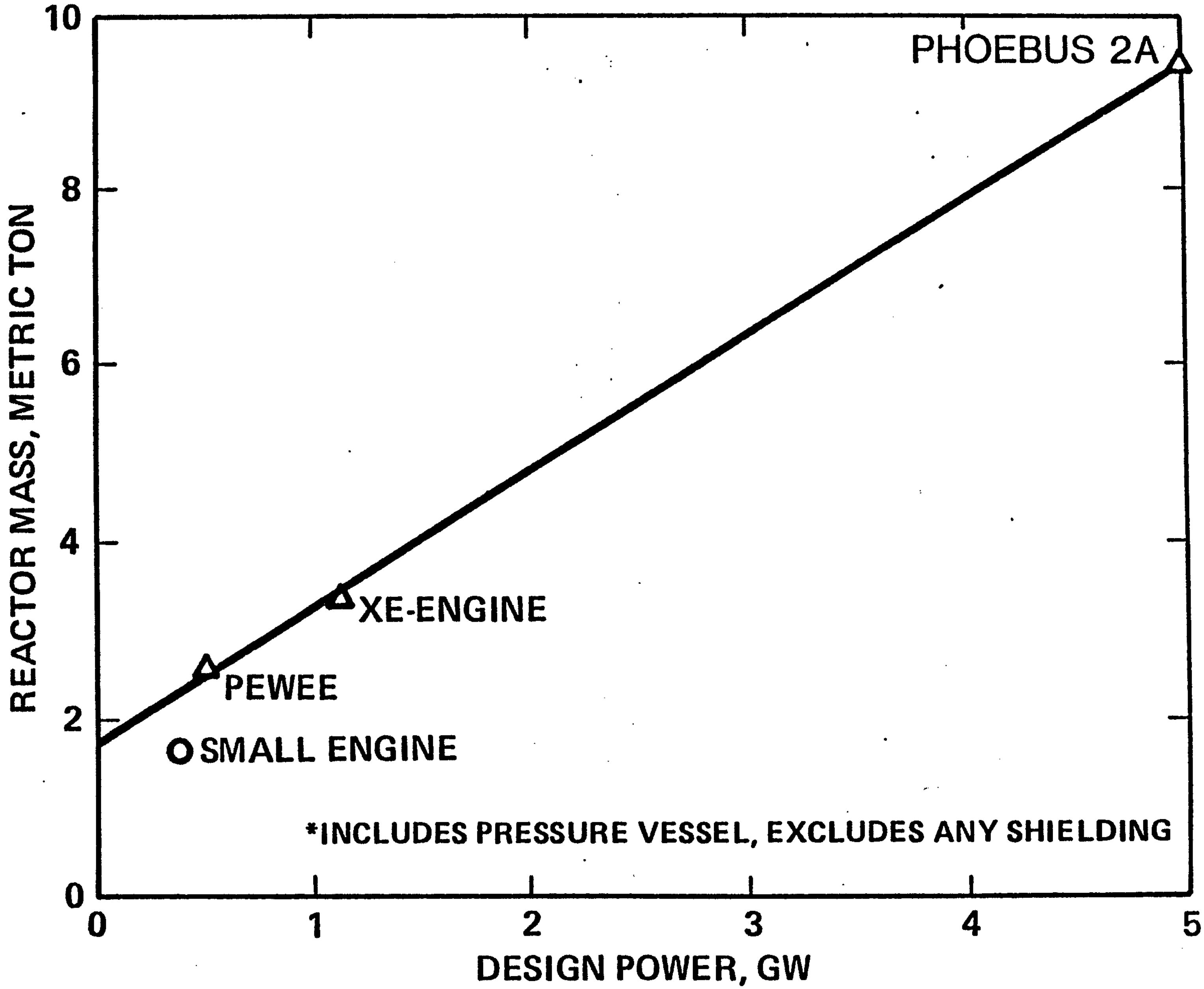
b. Capability for bimodal operation, and

c. Coolant expenditure for startup and shutdown during system tests.

Fuel element failure, e.g., cracking and release of a small piece or pieces from the elements, could lead to catastrophic failure of the turbine if pieces were ingested. If overall system reliability is to exceed 90%, turbine reliability must approach 100% in practical operating systems. Thus, the chance of turbine failure due to ingestion of fuel element pieces over the operating life must be very small. Establishing a 99% or so reliability level for NERVA turbines could be difficult and time-consuming.

FIG. 2.

REACTOR MASS vs DESIGN POWER



Bimodal operation is desirable, as discussed earlier. However, cw operation, even though at relatively low powers, will result in high fluence exposures for the fuel elements.

Under radiation exposure, the graphite elements will exhibit dimensional changes at a different rate than their ZrC coatings. The resultant stresses will probably crack the coatings. The resultant corrosion of the graphite matrix by hot H_2 could then lead to fuel element failure.

Neutron fluence to fuel elements will be on the order of 2 to 3×10^{21} over the operating life (~7 years) which will cause appreciable dimensional changes. A fuel irradiation test program appears necessary to investigate this question, and to demonstrate feasibility of NERVA-type fuel for bimodal operation. This program would involve thermal and H_2-cycling exposure under irradiation conditions.

Finally, substantial amounts of coolant will be expended for startups and cooldowns associated with systems tests. Startup of a core containing 2 metric tons of graphite, for example, would consume approximately 300 kg of H_2 in bringing it to steady-state temperature distribution and an equal amount in cooldown.

If system tests prove to be relatively frequent, e.g., several per year, the integrated H_2 coolant expenditure for startup and shutdown over the operating life would be on the order of 20 tons. This coolant expenditure would be in addition to that required for power generation during the system test, after the core reached steady state.

The FBR and RBR represent a different approach to high-power space reactors. These reactors are based on <u>direct</u> cooling of HTGR particulate fuel by H_2

or He gas. Instead of imbedding the fuel particles in graphite elements, as in NERVA or commercial HTGR power reactors, the particles are held in place and directly cooled.

Figure 2.7 shows the two types of fuel particles developed for HTGR's. In the TRISO type particle, the fissile kernel is UC or UO_2, or a mixture of the two, and is coated with several layers of ceramic material.

The inner layer is a porous pyrographite which holds the fission product gases generated in the fissile kernel. This layer is covered by an impervious layer of pyrographite, followed by a layer of SiC, with a final layer of pyrographite. The coating layers act as a miniature pressure vessel, holding in fission products.

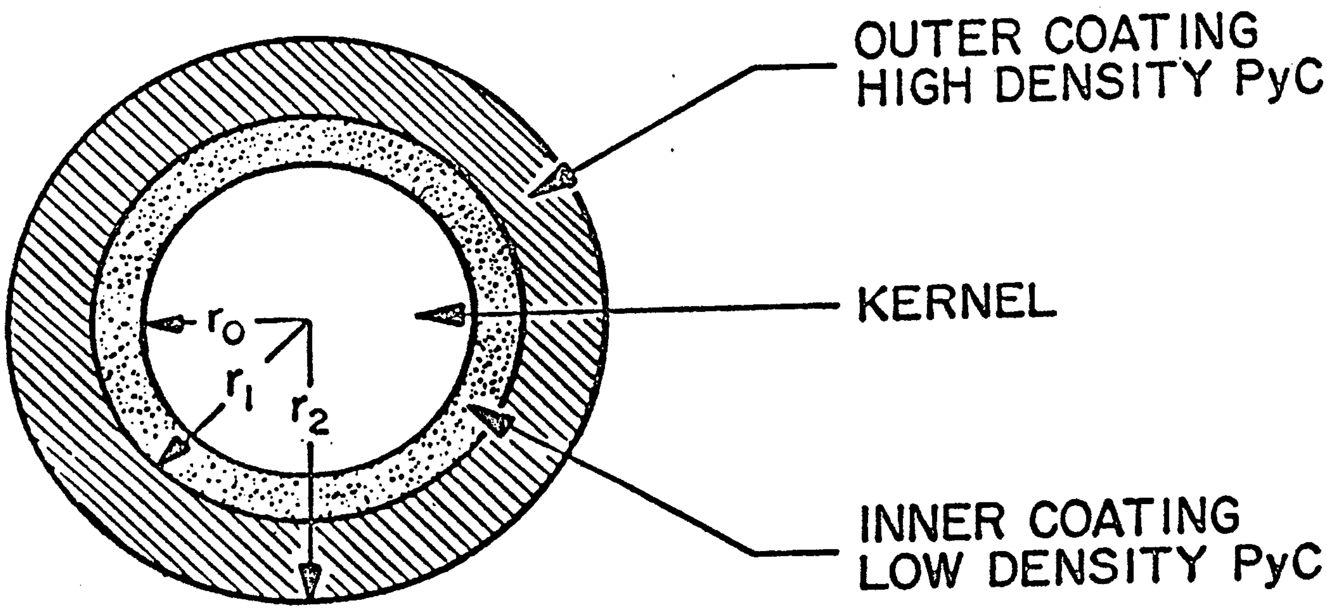
In the simpler BISO particle, the kernel is coated with a layer of porous pyrographite, followed by an outer impervious layer of pyrographite. BISO particles also act as pressure vessels to contain the fission products inside.

In commercial HTGR's, BISO particles correspond to breeder particles, in which ThO_2 kernel breeds in new fissile fuel. Fission burnup is low, and a relatively thin coat sufficies for particle integrity.

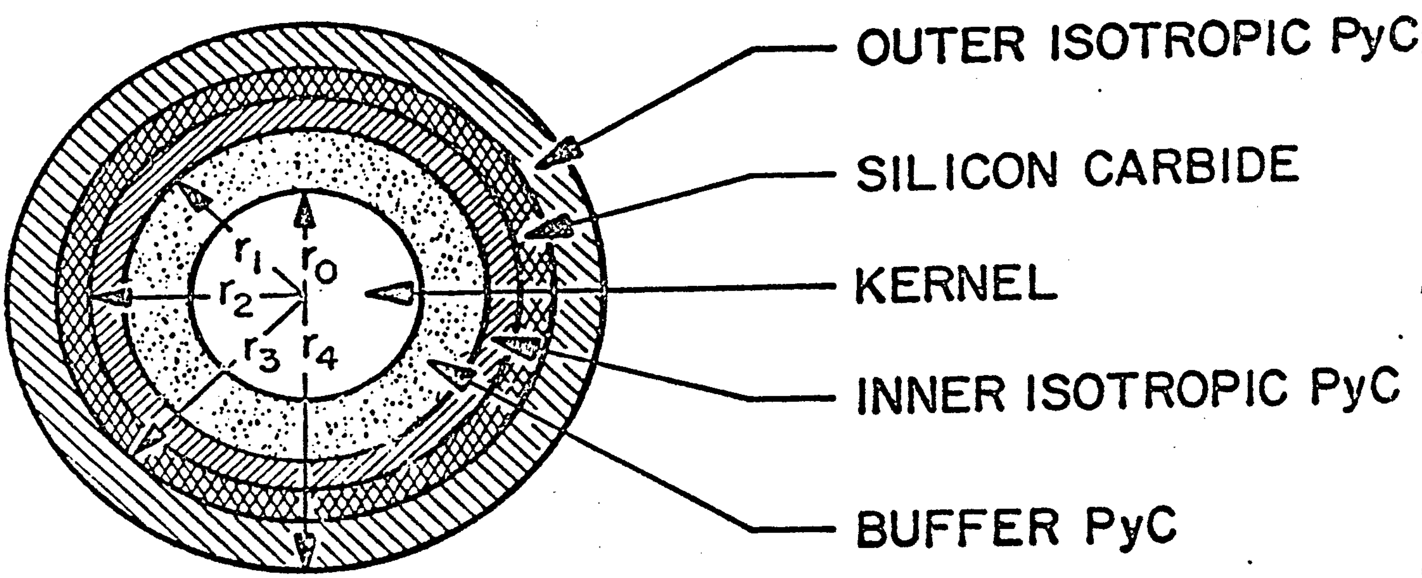
The TRISO particle has a fully-enriched kernel with high burnup (in some cases, exceeding 50%) of the contained fuel, so that the coating layers have to be substantially thicker to ensure particle integrity.

For space reactor applications, the TRISO-type particle would be used for cw generation reactors with substantial burnup. The BISO-type particle would be adequate for open-cycle reactors with low burnup of the enriched fuel, i.e., a few percent. In either case, only fully-enriched fuel would be used. Addition of breeding capability would increase reactor size and degrade neutronic performance.

FIGURE 2.7


OUTER COATING
HIGH DENSITY PyC
KERNEL
INNER COATING
LOW DENSITY PyC
r_0
r_1
r_2

(a)


OUTER ISOTROPIC PyC
SILICON CARBIDE
KERNEL
INNER ISOTROPIC PyC
BUFFER PyC
r_1
r_0
r_2
r_3
r_4

(b)

For bimodal reactors, the fuel particle design would depend on degree of burnup. For the 200/200 design discussed in the following section, burnup level is relatively small, about 3 to 4%, and the simpler BISO particle would be adequate.

The advantage of direct-cooled HTGR particulate fuel for space reactors are outlined in Figure 2.8.

There is an extensive background of well developed and characterized fuel technology. In some applications, commercial fuel could be directly used in FBR's. For other designs involving higher temperatures and/or contact with H_2 coolant, some modification would be necessary, but the technology background is good and technical risks appear small.

The performance with regard to power density, ΔT between fuel and coolant, temperature level, and startup rate are excellent. The power density of fuel scales inversely with characteristic size so that small diameter particles allow much higher power densities than larger diameter elements. For example, 1000 micron particles can have power densities a factor of ten higher than container size fuel elements.

The excellent retentivity and high burnup of HTGR fuel has been well demonstrated.

There is the potential for remotely unloading particle fuel from FBR/RBR reactors using pneumatic techniques. In zero-g conditions, this appears relatively straightforward. If it proves practical, it would have major safety and operational advantages.

Finally, the use of particle fuel permits relatively simple mechanical construction, particularly problems of core support and thermal expansion appear more tractable.

FIGURE 2.8

ADVANTAGES OF DIRECT-COOLED PARTICLE FUEL FBR/RBR REACTORS

- FUEL IS WELL DEVELOPED.
    - COMMERCIAL BISO OR TRISO FUEL IS SUITABLE FOR cw REACTORS.
    - ZrC COATED FUEL HAS BEEN TESTED AND APPEARS SUITABLE FOR PULSED OR BIMODAL REACTORS.
- HIGH-POWER DENSITY AND EXCELLENT HEAT TRANSFER WITH GAS-COOLED PARTICLE FUEL.
    - POWER DENSITY OF 1 TO 10 MW/LITER WITH He AND H_2 COOLING.
    - SMALL ΔT's (~10 TO 50 K) BETWEEN FUEL AND GAS COOLANT.
    - SMALL ΔT IN FUEL (FEW DEGREES K).
- LOW-THERMAL STRESS AND FAST STARTUP WITH SMALL DIAMETER FUEL.
    - PARTICLE BEDS BROUGHT TO FULL TEMPERATURE ($\geq$1500 K) IN 2 TO 3 SECONDS WITHOUT DAMAGE
- HIGH-TEMPERATURE CAPABILITY.
    - ~1500 TO 1800 K WITH He-COOLED cw SYSTEMS.
    - ~2000 TO 2500 K WITH H_2-COOLED PULSED SYSTEMS.

FIGURE 2.8 (Cont'd)

- HIGH BURNUP, LONG-LIFE CAPABILITY.
  - COMMERCIAL HTGR PARTICLES NOW OPERATE AT 1500 K FOR YEARS.
  - BURNUPS OF >50% HAVE BEEN ACHIEVED.
- EXCELLENT RETENTIVITY OF FISSION PRODUCTS (>99.99%).
- POTENTIAL FOR REMOTE UNLOADING AND REFUELING OF SPACE REACTORS.
- ALLOWS SIMPLE MECHANICAL DESIGN AND CONSTRUCTION OF REACTORS.

Figure 2.9 shows an isometric view of one configuration of the BFR (Fixed Bed Reactor). The HTGR fuel particles are held in an annular bed between two temperature porous frits. Coolant enters the particle bed throught the cool outer frit, passes radially inwards, and exits through the hot inner frit. Coolant distribution is by means of inner and outer radial plenums.

Neutrons are moderated and reflected by the outer cool external moderator (typically Be) and the inner hot moderator (graphite, BeO, or ZrC). They diffuse back into the fuel and are captured, sustaining the fission reaction. Control is by movable neutron absorbers in the outer reflector (one method is rotatable drums with poison on one side (B_4C) and moderator on the other).

Outlet coolant temperature limits are set by the fuel, inner moderator and frit. With helium coolant, the fuel is probably limiting, since graphite can go to very high temperatures. Non-metallic frits can be used, or metallic for the 200/200 design discussed in the next section, a W-Re frit is used, but is position <u>after</u> the inner moderator/reflector, to minimize its neutron absorbing effect.

With hydrogen coolant, carbide coated fuel and moderators would be used, and would probably limit outlet temperature to ~2000 to 2500 K.

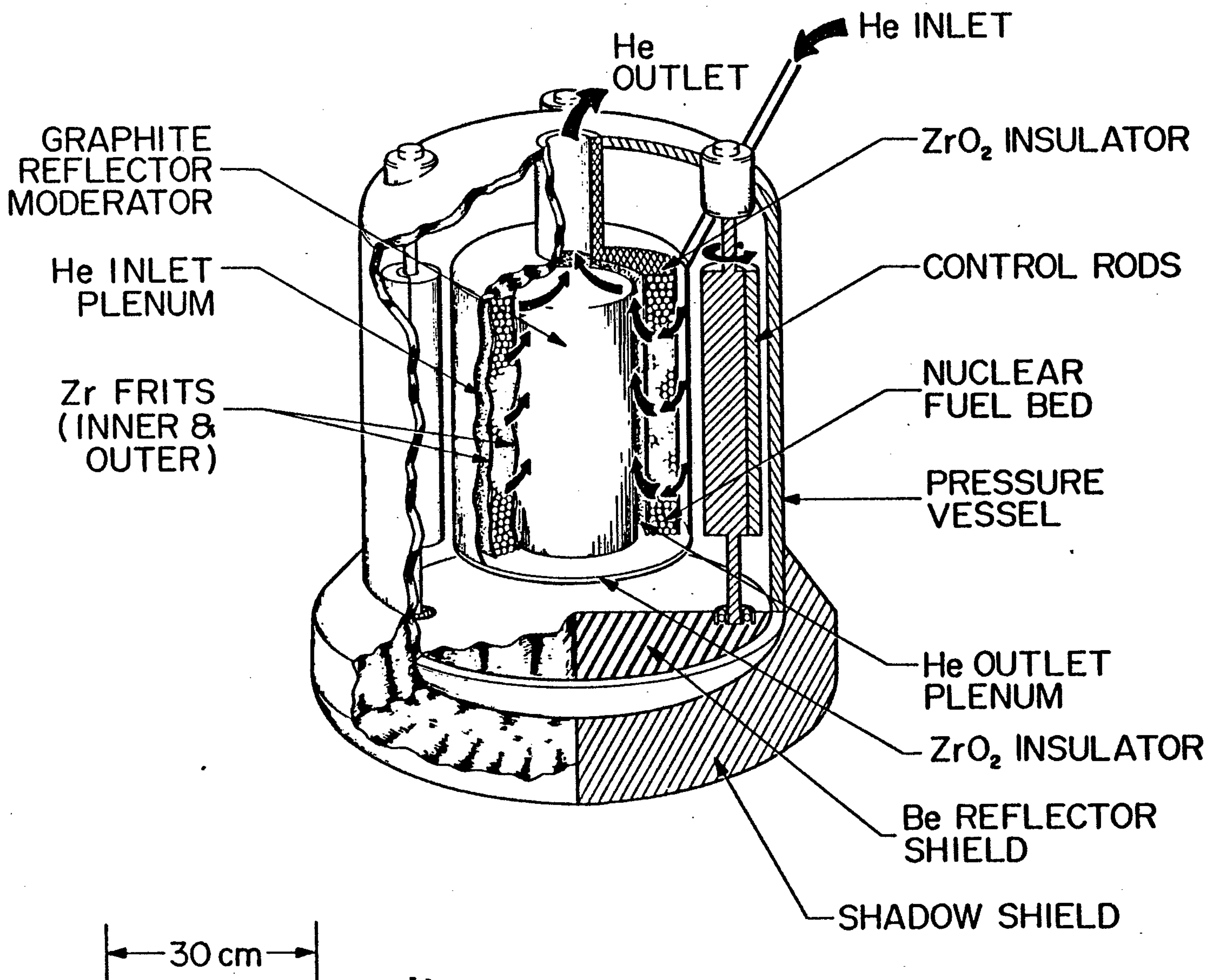
Other design configurations for the FBR are possible. These involve multi-element packed beds, and can be smaller and lighter than the example shown.

The RBR (Rotating Bed Reactor), shown in Figure 2.10, is similar to the FBR in many respects. It has an annular fuel bed, a porous outer frit, and an external moderator/reflector (probably Be). The chief difference is that the outer frit acts as a rotating basket (~1000 rpm) to hold the particle bed by centrifugal force against the coolant passing through. There is no inner frit

UNCLASSIFIED

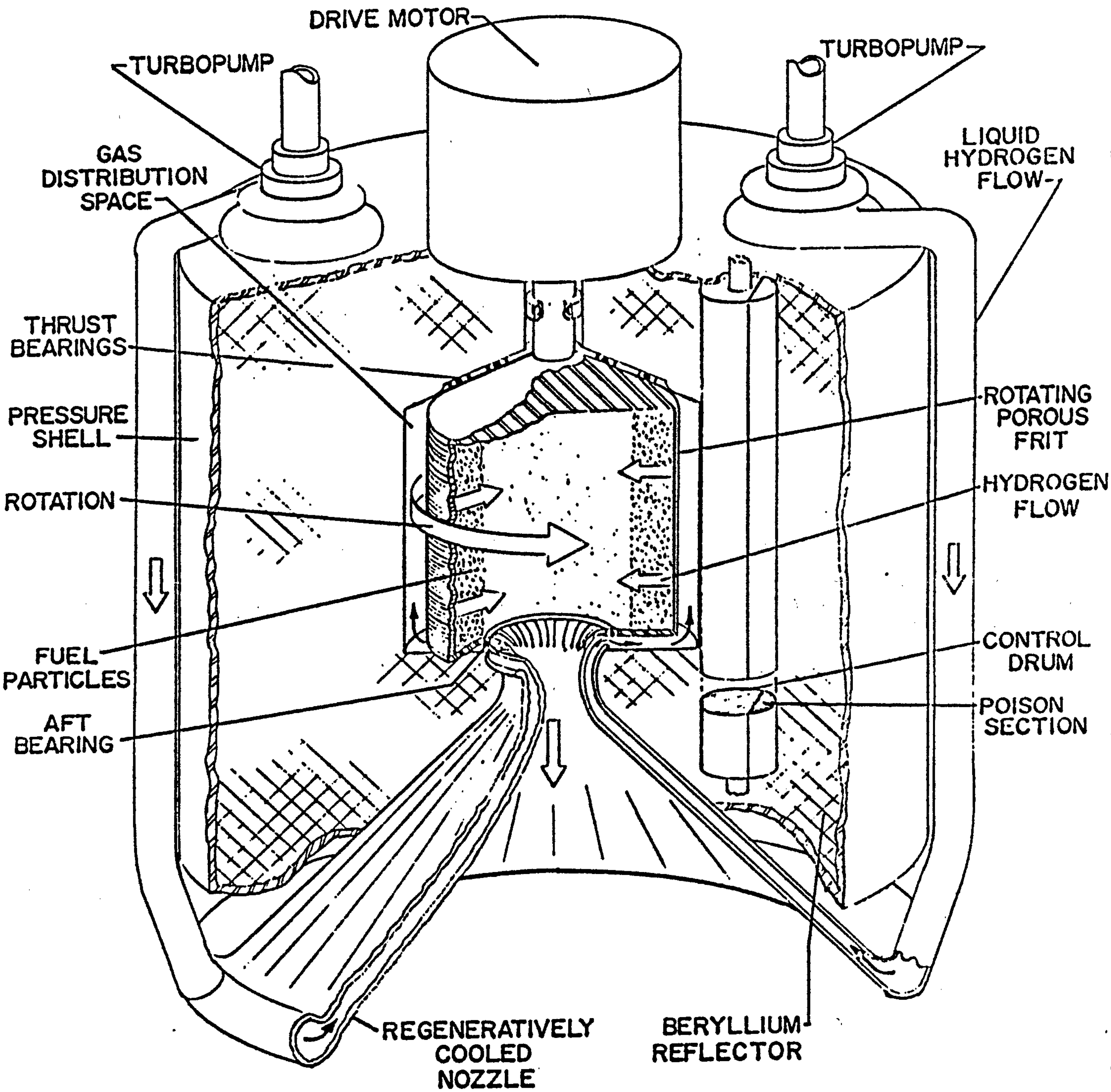
FIGURE 2.9

FIXED BED REACTOR (FBR)



UNCLASSIFIED

FIGURE 2.10



ROTATING FLUIDIZED BED ROCKET ENGINE

or moderator, and the coolant can achieve substantially higher outlet temperatures. The RBR is only contemplated for open-cycle operation for a few hours at most, and could achieve outlet temperatures of ~3000 K.

Tests with half-scale cold flow RBRs have demonstrated stable operation with the bed in the fully-settled, fully-fluidized, and partly-fluidized mode.

Fixed Bed Reactors can operate up to ~350 MW(th) with He cooling and ~1000 MW(th) with H_2 cooling. Figure 2.11 shows mass scaling of FBR's with power at maximum power overall length and diameter are slightly more than one meter.

Due to the heat transfer and lower pressure drop, RBR's can operate to substantially higher powers, e.g., up to ~5000 MW(th) at approximately the same size and weight as a 1000 MW(th) FBR.

Figure 2.12 summarizes the time/temperature/power ranges expected for FBR's and RBR's. The FBR is more versatile, and can be used for open, closed, and bimodal applications. The RBR is mechanically more complex and is best suited for shorter life, open-cycle applications.

Figure 2.13 compares NERVA, FBR, and RBR for high power space reactor applications. Overall, the FBR appears best suited for the power levels, operating lifetimes, and generation capabilities likely to be required for high power space nuclear systems.

For open-cycle generation with turbines, inlet temperature capability will probably be limiting, rather than reactor temperature, so that all three options appear satisfactory.

With open-cycle MHD generation, however, maximum temperature capability is very important. Outlet temperatures must be above ~2800 K for good

FIGURE 2.11

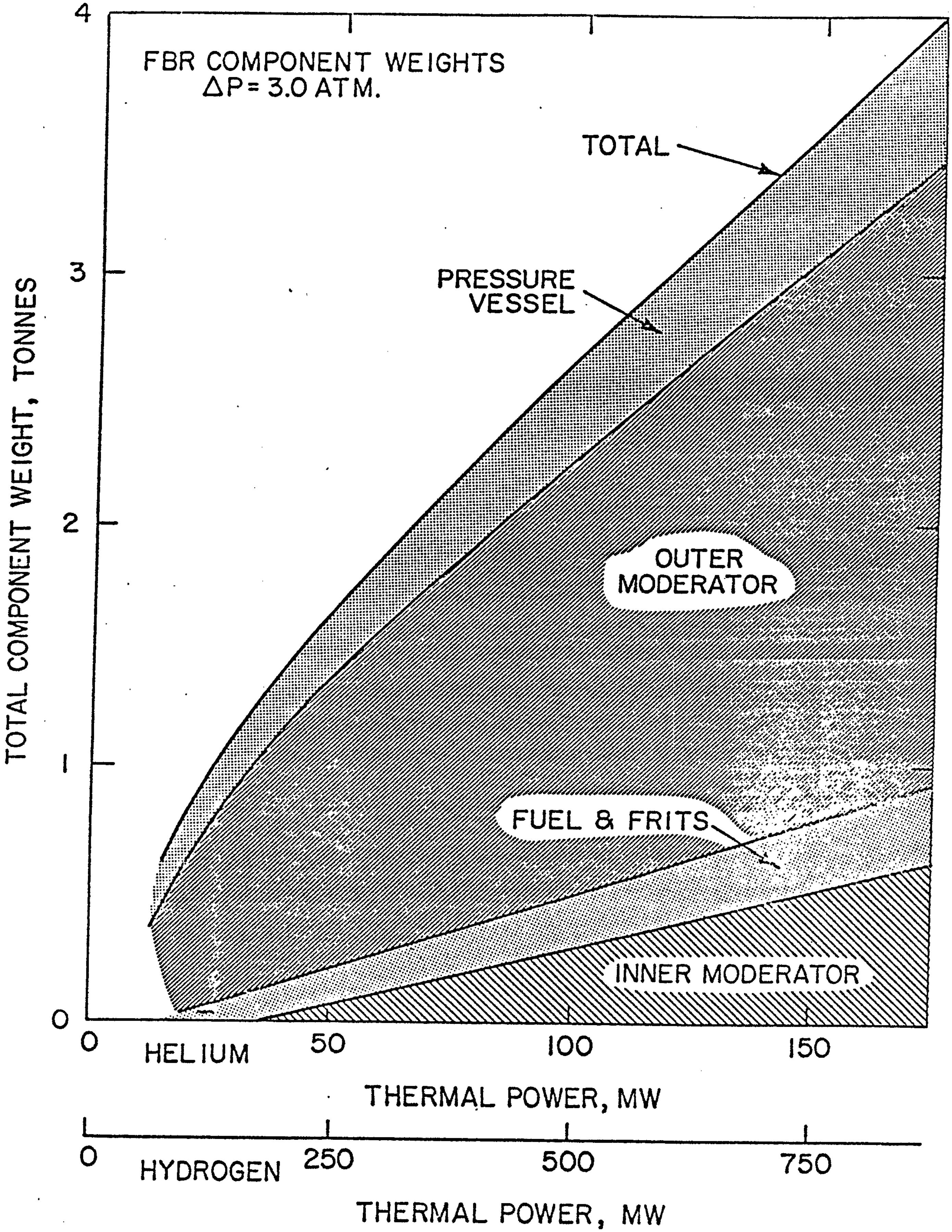

FBR COMPONENT WEIGHTS
ΔP = 3.0 ATM.
TOTAL
PRESSURE VESSEL
OUTER MODERATOR
FUEL & FRITS
INNER MODERATOR
TOTAL COMPONENT WEIGHT, TONNES
0
1
2
3
4
0
HELIUM
50
100
150
THERMAL POWER, MW
0
HYDROGEN
250
500
750
THERMAL POWER, MW

FIGURE 2.12

OPERATING RANGES OF FBR's AND RBR's

MAXIMUM CAPABILITY	OPEN CYCLE FBR	OPEN CYCLE RBR	CLOSED CYCLE RBR
Power, MW(e)	500	2000	100
Time, Hours	10	5	$4x10^4$
Temperature, K	2500	3000	1800

FIGURE 2.13

COMPARISON OF HIGH POWER OPTIONS

CAPABILITY	NERVA	FBR	RBR
MAXIMUM POWER WITH TURBINES MW(e) WITH MHD, MW(e)	 400 2000	 400 ---	 400 2000
MAXIMUM COOLANT TEMPERATURE (OPEN CYCLE)	2500	2500	3000
BIMODAL FEASIBILE	?	YES	NO
STARTUP TIME, sec	~30	~2 to 3	~2 TO 3
SIZE AND WEIGHT FOR 400 MW(e)	~1 m^3, 3 MT	~1 m^3, 3 MT	~1 m^3, 3 MT
FUEL INTEGRITY WITH TURBINES	?	GOOD	GOOD
REACTOR DEVELOPMENT STATUS	GROUND TESTED	CONCEPT	CONCEPT
FUEL TECHNOLOGY STATUS	?		
H_2 CONSUMPTION STARTUP/SHUTDOWN	HIGH	LOW	LOW
MECHANICAL COMPLEXITY	MODERATE	LOW	MODERATE

efficiency, preferably 3000 K or greater for compactness and generator performance. The RBR appears clearly favored if MHD is used.

For generation with turbines, equipment size and weight will probably limit generation capability to a few hundred MW(e) at most. Above this level, MHD will be required.

The three options have roughly comparable overall size and weight for the same power level. In practice, the RBR will be somewhat smaller and lighter than the FBR, which, in turn, will be somewhat smaller and lighter than NERVA. The differences will not be significant, however, since system weight will be strongly dominated by stored H_2 and power conversion equipment.

Startup time appears to be a major difference between the particle bed reactors and NERVA. In the applications of interest, short startup time will be very important, particularly since the power source will probably have to come up to full power and down a substantial number of times (though not always from a dead cold condition).

Hydrogen consumption during startup and shutdown will be much greater for NERVA reactors. In the FBR and RBR, most of the reactor mass is in the cool outer reflector, and only the fuel and interior regions heat up. Hydrogen consumption for a NERVA startup/shutdown (i.e., that required to just bring the core to a steady state temperature distribution from a cold start, and not including consumption during running) will be about 0.5 metric ton. The amount for the FBR and RBR will be much smaller, i.e., 10 to 20% of that.

The suitability of NERVA fuel for turbine generation and/or bimodal operation is uncertain at this point. Reliability against having pieces of fuel elements ingested into the turbine must be very high. NERVA graphite fuel is subject to corrosion by H_2 if ZrC coatings locally fail, and could result in parts of elements breaking off. In the FBR, the fuel particles are all ZrC with a small UC/ZrC kernel and have small overall diameter. In addition, the hot inner frit will prevent fragments from reaching the turbines. (In the 200/200 design discussed in the next section, the inner frit also protects against failure of the inner ZrC moderator.) In the RBR, centrifugal force functions in a similar manner to the frit in preventing fragments from reaching the turbine.

The suitability of NERVA fuel for bimodal operation has to be established, since irradiation exposure may cause degradation of the protective ZrC coatings. The FBR appears to have no potential go/no-go issues relating to bimodal operation.

Finally, NERVA was successfully ground tested, and has the background of a large R&D expenditure. However, NERVA would have to be substantially modified and retested for electric power applications. The FBR has not been tested as a reactor. However, it has an extensive materials technology base, including a great deal of work on the fuel. It is a mechanically simple reactor and could probably be developed as rapidly as an updated NERVA. The RBR is somewhat more mechanically complicated. However, its development time should not be much longer than that of either the FBR or NERVA.

3. 200/200 BIMODAL FBR SYSTEM

A preliminary design of a 200 MW(e) pulsed/200 kW(e) cw FBR bimodal system has been prepared as an example of future capabilities of space nuclear power. The 200 MW(e) output would be based on open-cycle generation with H_2 coolant, while the 200 kW(e) output would be based on a closed-Brayton cycle, He-cooled generation. The same FBR reactor would be used for both generation modes.

The overall layout of the power system is shown in Figure 3.1. The power train consists of a framework 13 meters in length and 3 meters in width (maximum), which holds the reactor, shield, piping, H_2 pumps, two open-cycle turbines and generators, two closed-cycle turbines and generators (for redundancy), and controls.

The total mass of the power train is 21 metric tons. It can be carried as a single unit in the Shuttle bay.

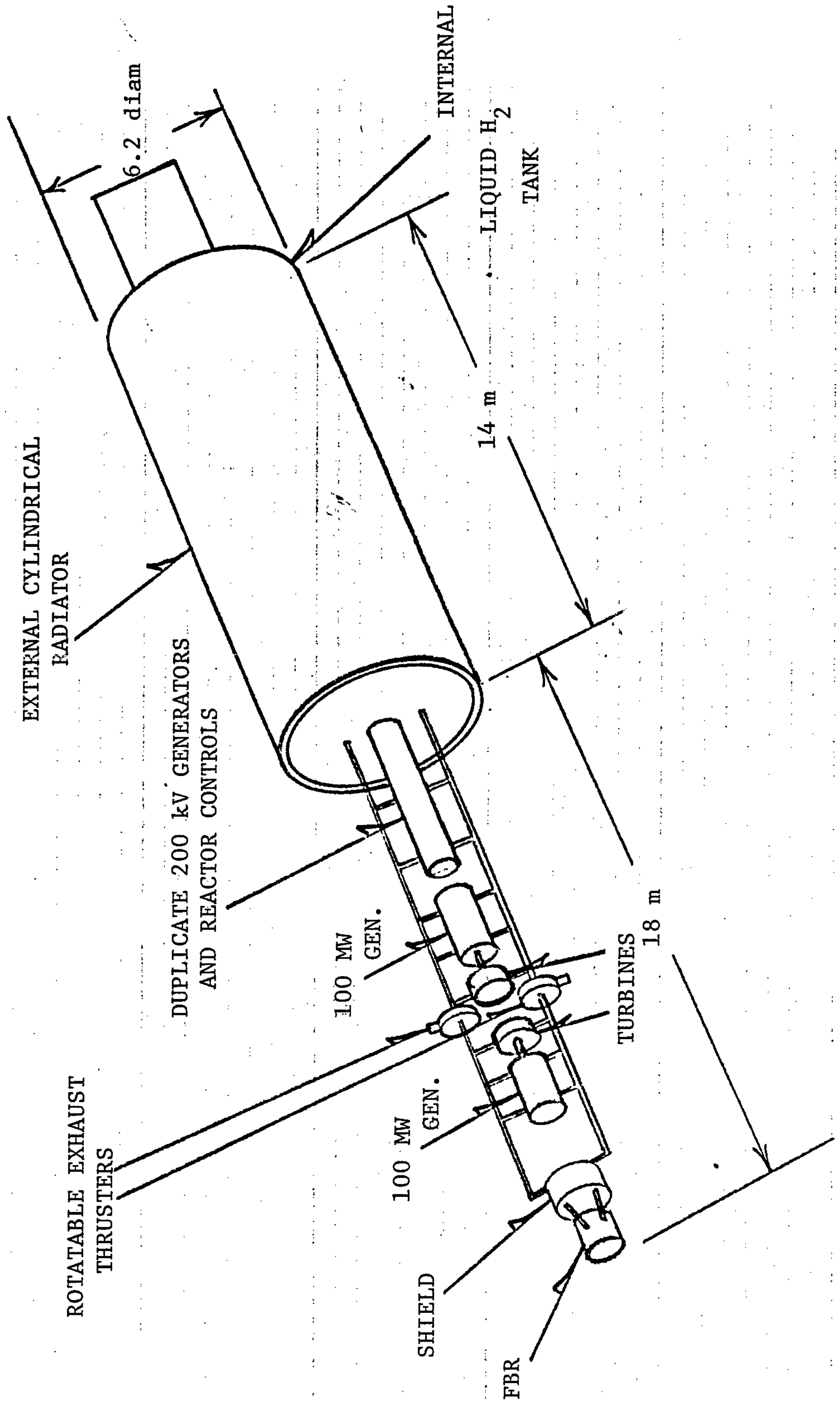
The power train is mated to a H_2 supply tank carrying sufficient liquid H_2 (27 metric tons) for 100 MW(e) hours of pulsed generation. The reactor/power system is conservatively designed for 2000 K exit temperature in the open-cycle mode. Higher-exit temperatures appear possible, depending on fuel performance and turbine design. An exit temperature of 2500 K would reduce H_2 requirements by 20%.

The 100 MW(e) hours value can be increased or decreased by adjustments in the H_2 tankage volume.

The nominal H_2 tank is 6 meters in diameter and 13 meters in length. The outer cylindrical surface consists of a radiator panel for the 200 kW(e) closed-Brayton cycle. This panel operates at an average temperature of ~550 K, and is thermally insulated from the H_2 tank by multi-layer super insulation. Heat

FIGURE 3.1

OVERALL LAYOUT OF POWER SYSTEM



leak through this insulation is very low, on the order of a few watts per square meter. An intermediate thermal station is positioned between the radiator panel and the 20 K H_2 tank to intercept thermal leakage. The end of the tank is a low-temperature panel that radiates this energy to space. Its temperature depends on design and orientation relative to sun and the earth, but is on the order of 200 K.

The H_2 supply, counting tankage and radiator panel weighs approximately 33 metric tons. The payload platform is located on the opposite end of the H_2 tank from the power train. Its size and weight are not specified, since they will depend on the particular technology and mission being considered.

The H_2 tank, shield, and distance from the reactor will allow the payload to be manned, if desired.

The H_2 tank is somewhat larger and heavier than the Shuttle capacity. A multiple tank could be designed to be Shuttle compatible, or more likely, the tank and payload could be lifted by a Shuttle derived lift vehicle. The power train could also be lifted as part of a unitized payload, if lift and length capacity were sufficient.

If the power train had to be lifted separately by the Shuttle, it could be mated to the H_2 tank through 3 coolant connections--liquid H_2 supply line from the tank, and two He lines to and from the radiator panel.

Figure 3.2 summarizes the main features of the 200/200 FBR Bimodal System.

Figure 3.3 shows a cross section and elevation view of the FBR reactor for the 200/200 system. Main features of the reactor are summarized in Figure 3.4. The required materials use available or near-term technology. The fuel particles are a relatively small extrapolation from existing technology, for

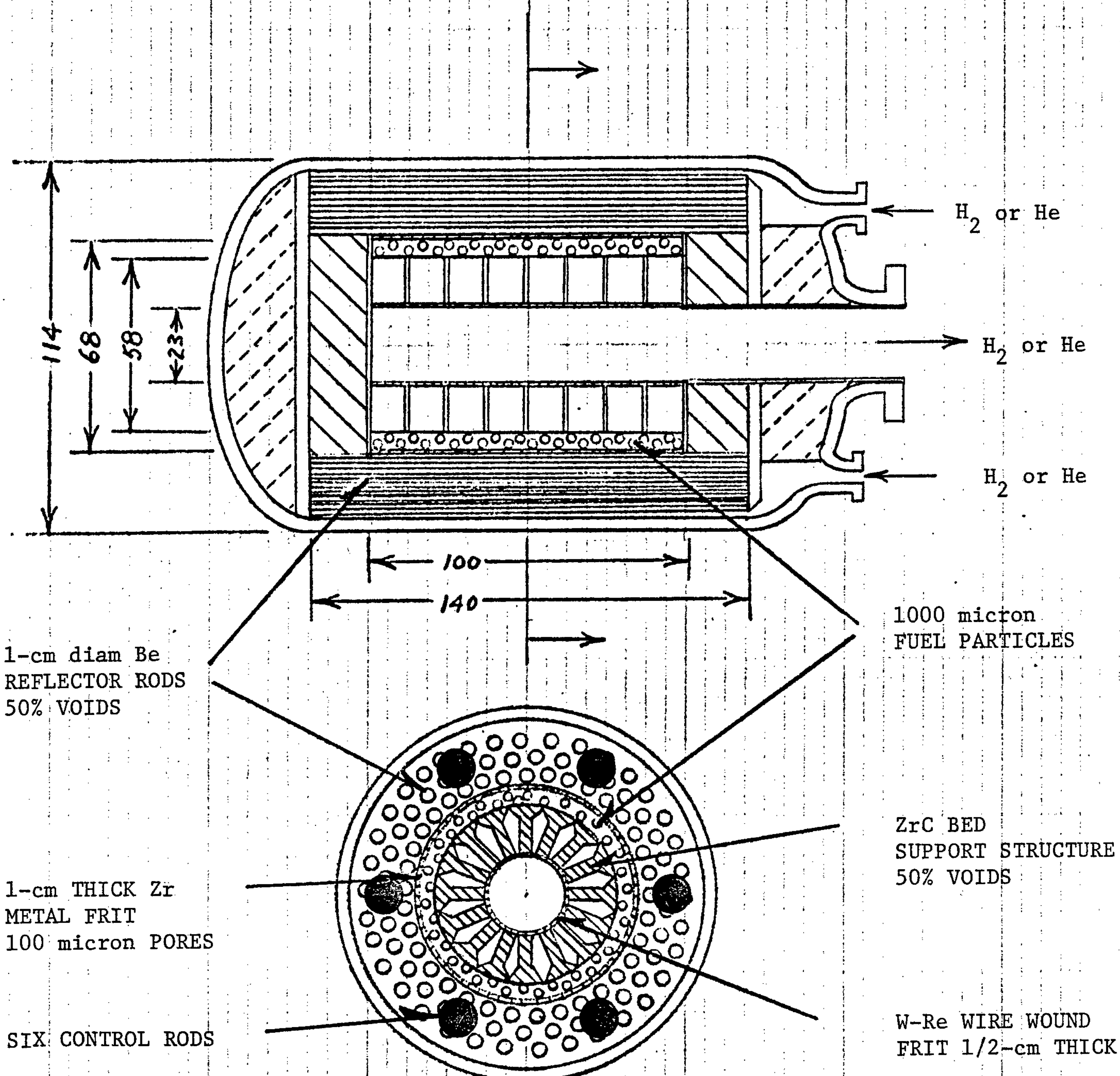
FIGURE 3.2

MAIN FEATURES OF THE 200/200 BIMODAL FBR SYSTEM

- UNITIZED POWER TRAIN
  - REACTOR AND ALL POWER EQUIPMENT IN SINGLE LINEAR FRAME,
  - POWER TRAIN DIMENSIONS 13 METERS x 3 METERS (MAXIMUM).
  - POWER TRAIN MASS 21 METRIC TONS.
  - CAN BE CARRIED IN SHUTTLE.
- POWER TRAIN MATED TO H_2 TANKAGE AND PAYLOAD.
  - THREE COOLANT SUPPLY CONNECTIONS.
- RADIATOR PANEL FOR cw GENERATION ON OUTER CYLINDRICAL SURFACE OF H_2 TANK.
  - THERMALLY INSULATED FROM H_2 TANK.
- H_2 TANK SIZED FOR 100 MW(e) HOURS OF PULSED GENERATION.
  - 33 METRIC TONS TOTAL WEIGHT INCLUDING TANKAGE AND RADIATOR PANEL.
  - SIX METER DIAMETER, 13 METER LONG.
  - CARRIED BY SHUTTLE DERIVED VEHICLE.
    - PAYLOAD AND POWER TRAIN MAY ALSO BE CARRIED AS UNIT WITH TANK.
- THRUST DEFLECTORS ALLOW GENERATION OF THRUST DURING ELECTRIC GENERATION IF DESIRED.
  - PLATFORM ACCELERATION $\sim$0.1 g

FIGURE 3.3

CROSS SECTIONS OF 200/200 BIMODAL FBR



DIMENSIONS IN cm

FIGURE 3.4

MAIN FEATURES OF 200/200 BIMODAL FBR REACTOR

- ZrC COATED BISO PARTICLES.
  - UC/ZrC KERNEL.
  - ~1000 MICRON DIAMETER.
  - 4% BURNUP OF ^{235}U.
  - 1500 K FOR 7 YEARS (He).
  - 2000 K FOR 0.5 HOURS (H_2).
- Be (OUTER) AND ZrC (INNER) MODERATOR/REFLECTORS.
- Zr (OUTER) AND W-Re (INNER) FRITS.
- FUEL BED DIMENSIONS OF 70 cm (DIAM) AND 100 cm (LENGTH).
- OVERALL REACTOR DIMENSIONS OF 1.2 m (o.d.) AND 1.8 m (LENGTH).
- INCONEL PRESSURE VESSEL.
- NEUTRON ABSORBER CONTROL (B_4C) IN OUTER MODERATOR/REFLECTOR.

example. Materials and fuel will require testing and validation in high-temperature H_2.

The reactor is sized by H_2 pressure drop considerations in the pulsed-power mode. Pressure drop in the 200 kW(e) cw mode are very small, and the reactor size would shrink greatly if only cw generation were called for.

Some type of valve will be required to seal off the H_2 vent to space during closed-cycle operation with He. This must be capable of quick opening (i.e., a couple of seconds); and resealable. Substantial gas breakage can occur, as long as the leak rate is below ~10 torr liters/sec (~60 kg/year). This is a high allowable leak rate, compared to standard vacuum systems.

Mechanical and freeze valves have been examined. Both appear practical, and initial demonstration of the freeze value concept has been carried out.

Figure 3.5 lists the principal parameters of the 200/200 Bimodal System.

This Bimodal FBR approach can be scaled to other power levels, depending on requirements. Figure 3.6 outlines the power ranges over which it could apply, and the design changes that would be necessary. Power levels could be handled by a cw nuclear power source. The FBR and turbines are probably not suitable for power levels above about 400 MW(e). For these power levels, one would have to go to a NERVA or RBR with MHD conversion. One would probably have to operate only in the open-cycle mode, with a separate reactor for cw power.

FIGURE 3.5

PRINCIPAL PARAMETERS OF THE 200/200 BIMODAL FBR

- 200 MW(e) PULSED OUTPUT.
- 200 kW(e) cw STATION KEEPING OUTPUT.
- H_2 COOLANT FOR PULSED OPEN-CYCLE OPERATION.
    - 60 atm INLET PRESSURE.
    - 3.0 atm ΔP THROUGH REACTOR.
    - ~1 atm OUTLET PRESSURE FROM TURBINE.
    - ~40% CYCLE EFFICIENCY, 15 kg H_2/sec.
    - 2000 K INLET TEMPERATURE TO TURBINE.
- He COOLANT FOR cw CLOSED-CYCLE OPERATION.
    - 30 atm INLET PRESSURE.
    - 0.3 atm ΔP THROUGH REACTOR.
    - 11 atm OUTLET PRESSURE FROM TURBINE.
    - ~33% CYCLE EFFICIENCY
    - 1500 K TURBINE INLET TEMPERATURE, 950 K INLET REACTOR TEMEPRATURE.
    - RECOUPERATED BRAYTON CYCLE.
    - 750 K INLET RADIATOR TEMPERATURE.
    - 450 K COMPRESSOR INLET TEMPERATURE.

FIGURE 3.5 (Cont'd)

- SYSTEM WEIGHTS
  - REACTOR, 2.5 METRIC TONS.
  - SHIELD, 6.6 METRIC TONS.
  - OPEN-CYCLE TURBINES & GENERATORS, 8.0 METRIC TONS.
  - CLOSED-CYCLE TURBINES & GENERATORS & RECUPERATORS, 0.8 METRIC TONS.
  - PIPING AND FRAMEWORK, 2.0 METRIC TONS.
  - CONTROLS, 1.0 METRIC TONS.
  - TOTAL, 20.9 METRIC TONS.

FIGURE 3.6

SCALABILITY OF THE 200/200 BIMODAL FBR

← DECREASING POWER		INCREASING POWER →
• PULSE POWER DOWN TO 10 TO 20 MW(e) • cw SYSTEMS MORE ATTRACTIVE BELOW ~10 TO 20 MW(e) • 27 TONS H_2 GIVES 5 HOURS AT 20 MW(e)	200/200	• PULSE POWER UP TO ~400 MW(e) • LIMITED BY TURBINE/GENERATORS & CORE SIZE • 27 TONS H_2 GIVES 15 MINUTES AT 400 MW(e)	↑ PULSED POWER
• cw POWER DOWN TO FEW kW(e) • NO SIGNIFICANT REDUCTION IN SYSTEM SIZE AND WEIGHT - CONTROLLED BY PULSE POWER REQUIREMENTS		• cw POWER UP TO ~2 MW(e) WITH CONVENTIONAL RADIATORS • HIGHER POWERS REQUIRE ADVANCED LIGHTWEIGHT RADIATOR (e.g., LIQUID DROP RADIATOR) • PULSE POWER COMPONENTS STILL DOMINATE (EXCEPT FOR RADIATOR) • REFUELING CAPABILITY REQUIRED FOR POWERS ABOVE 3 TO 4 MW(e) cw	cw POWER ↓

4.0 TECHNOLOGY STATUS

Figure 4.1 summarizes highlights of the relevant technology for the FBR reactor. The fuel technology base is well developed. Some modification of the commercial fuel to ZrC coatings would be necessary. Such fuel has been fabricated and tested by GA Technologies at high temperature and burnup, with very good results.

Preliminary thermal-hydraulics of electrically heated packed particle beds have demonstrated the capability to operate at high power densities, even at low-coolant pressures, i.e., one atm. Pressure drops were as predicted.

There is background data on the properties of beryllium, zirconium, tungsten-rhenium, and Inconel, both irradiated and non-irradiated. Data on ZrC behavior under irradiation may be available, but has not been found yet. In the FBR designs, ZrC is used under low-stress conditions, and is contained by the high-temperature frit.

Control drums have been developed and extensively tested for the SNAP program. The FBR would use similar control mechanisms.

Scoping studies of FBR's have been carried out to examine likely operating regimes. Neutronics, thermal hydraulics, and mechanical design aspects have been studied.

Figure 4.2 summarizes highlights of the technology status of turbine-generator systems for space nuclear systems. There is substantial background experience on both open- and closed-cycle turbines. The NASA LeRc program, demonstrating long-life operation of a 10 kW(e) prototype closed-cycle turbine for space applications was very successful. The turbine operated for an integrated lifetime of more than 4 years with no major problems.

FIGURE 4.1

FBR REACTOR TECHNOLOGY STATUS

- FUEL
  - FUEL DEVELOPED FOR CLOSED-CYCLE APPLICATIONS (OPERATES FOR YEARS AT 1500 K).
  - CAN BE MODIFIED FOR OPEN CYCLE.
  - ZrC COATED FUEL TESTED AT 1800 K FOR 6 MONTHS WITH HIGH BURNUP -- GOOD PERFORMANCE.
- THERMAL HYDRAULICS.
  - ELECTRICALLY HEATED PARTICLE BEDS DEMONSTRATED AT ~1 MW/LITER WITH 1 atm He COOLANT.
    - ΔP's AS PREDICTED.
- MATERIALS.
  - DATA ON MECHANICAL AND IRRADIATOR BEHAVIOR OF Be, Zr, W-Re, AND INCONEL (PRESSURE VESSEL).
- CONTROL MECHANISMS.
  - SNAP CONTROL DRUMS EXTENSIVELY TESTED.
- SCOPING STUDIES CARRIED OUT (NEUTRONICS, THERMAL-HYDRAULICS, MECHANICAL DESIGN).

FIGURE 4.2

TURBINE-GENERATOR TECHNOLOGY STATUS

- OPEN-CYCLE H_2 TURBINES.
  - MK-10 TURBINE EXPERIENCE (50 MW(e) EQUIVALENT).
  - GE HIGH TEMPERATURE (2500 K) H_2 COOLED BLADE TURBINE EXPERIENCE (2 MW(e).
  - AIRCRAFT TURBINE BACKGRUND.
  - HIGH TEMPERATURE CARBON/CARBON BLADE PROGRAM.
  - CERAMIC BLADE TURBINE PROGRAMS.
- CLOSED-CYCLE INERT GAS TURBINES.
  - NASA CLOSED CYCLE 4-YEAR 10 kW(e) TURBINE TEST.
  - GARRETT BRU & MINI BRU TEST PROGRAMS.
  - SELZER CLOSED-CYCLE He TURBINE PLANT.
- SUPERCONDUCTING GENERATORS.
  - APL 20 MW(e), 1000 kg FAST RAMP TURBINE PROGRAM.
    - ROTOR COILS TESTED.
  - MIT & WESTINGHOUSE PROGRAMS IN SUMPERCONDUCTING GENERATORS.
  - EXTENSIVE BACKGROUND IN SUPERCONDUCTING MAGNETS AND HELIUM REFRIGERATORS.

The open-cycle turbine driving the liquid H_2 pump for the space Shuttle main engine delivers ~50 MW and is within a factor of two of the unit output for the 200/200 design.

The Shuttle turbine operates at substantially lower temperature than the 2000 K assumed in the 200/200 design. In the early 1960's, GE operated a 2 MW(e) turbine with H_2-cooled blades at inlet temperatures up to 2500 K for relatively long periods (hours). Maximum blade temperatures were only about 700 K. At the higher pressure for a space power system (about a factor of ten higher) cooling will not be as effective, but the technique should still allow inlet temperatures of ~2500 K.

The APL superconducting generator approaches the desired space generator relatively closely. APL estimates that the 20 MW(E) capacity could be increased to ~50 MW(E) by making the rotor and starter windings somewhat longer, but using the same basic size machine. With a somewhat larger diameter, the generator could be scaled to ~100 MW(e), at a unit weight of ~0.02 kg/kW(e). The generator is designed to ramp to full power in approximately a second. The rotor field coils have been tested under simulated operating conditions, and perform very well. A full-scale rotating test is expected within a year.

5. RD&D REQUIREMENTS

Figure 5.1 lists the major milestones for the reactor and power conversion system. For the latter, R&D would build on the background in turbines and generators, both open and closed cycle. After demonstration of the APL 20 MW(e) superconducting generator, engineering design of 100 MW(e) components for the open-cycle mode would be carried out. The components would be tested by using a non-nuclear energy source, and then integrated with the reactor in a ground-based prototype test.

A similar strategy would be followed for the closed-cycle power system. Extensive experience exists on closed-Brayton cycles. An engineering design of the actual system would be carried out, followed by a non-nuclear system test, and final integration with the reactor.

For the reactor, fuel, and materials, validation would be carried out at an early stage, along with thermal-hydraulic tests of a partial core sector, and reference and engineering designs.

Fuel unload/load experiments would be carried out to see if this capability were practical. If it were, it could have major benefits for safety and long-life capability.

Safety analyses would be carried out throughout the entire program, becoming more detailed as the designs evolved and became more defined.

Critical experiments would check neutronic analysis, and would start in 2 to 3 years after program initiation.

A full-scale ground-based prototype, together with power conversion system would be tested after the above milestones were achieved. Following this, flight qualified reactors could be designed and tested.

FIGURE 5.1

RD&D REQUIREMENTS

MAJOR REACTOR MILESTONES

- FUEL VALIDATION IN H_2 AT PROJECTED TEMPERATURE AND BURNUP.
- COMPATABILITY TESTS BETWEEN FUEL, HOT FRIT, AND INNER MODERATOR IN H_2 AND He.
- THERMAL-HYDRAULIC EXPERIMENTS ON SECTOR OF REACTOR CORE FOR OPEN- AND CLOSED-CYCLE OPERATION.
- DEMONSTRATION OF ISOLATION VALVE (BIMODAL).
- REFERENCE AND ENGINEERING DESIGNS OF REACTOR.
- FUEL LOAD/UNLOAD DEMONSTRATION.
- CRITICAL EXPERIMENT (INCLUDING BURNUP EFFECTS).
- SAFETY ANALYSES.
- FULL-SCALE GROUND-BASED PROTOTYPE.
- FLIGHT QUALIFIED REACTOR.

FIGURE 5.1 (Cont'd)

MAJOR REACTOR MILESTONES

- DEMONSTRATION OF 20 MW(e) APL SUPERCONDUCTING GENERATOR (UNDER WAY).
- ENGINEERING DESIGN OF 100 MW(e) SUPERCONDUCTING GENERATOR.
- ENGINEERING DESIGN OF 100 MW(e) H_2 TURBINE.
- DEMONSTRATION OF 100 MW(e) OPEN-CYCLE GENERATION WITH NON-NUCLEAR SOURCE.
- ENGINEERING DESIGN OF 200 MW(e) CLOSED-CYCLE TURBO/GENERATOR SYSTEM.
- DEMONSTRATION OF 200 kW(e) GENERATION WITH NON-NUCLEAR SOURCE.
- FULL-SCALE GROUND-BASED PROTOTPE WITH REACTOR.
- FLIGHT QUALIFIED REACTOR POWER SYSTEM.

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